

TBCC TSTO Design for the NASA-AFRL Joint System Study

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ABSTRACT

NASA and the Air Force Research Laboratory are involved in a Joint System Study (JSS) on Two-Stage-to-Orbit (TSTO) vehicles. The JSS will examine the performance, operability and uncertainty of unmanned, fully reusable, airbreathing-based TSTO launch vehicle concepts. NASA is providing a concept using turbine-based combined cycle (TBCC) propulsion on the booster stage and an all-rocket orbiter. The Air Force supplied two vehicle concepts, both utilizing an all-rocket booster; one with an all-rocket orbiter, the other using a rocket-based combined cycle orbiter. For NASA, this study is being used for tool assessment and development, and to identify generic technology gaps, not to choose vehicle types or concepts. This presentation starts with an overview of the major JSS ground rules and assumptions. Second, the NASA TSTO concept, Reusable Airbreathing Launch Vehicle – iteration B (RALV-B) is introduced, including its mission profile and, the vehicle (booster and orbiter) layout and packaging. The high speed propulsion concept is then briefly discussed, including the work performed and lessons learned. The low speed TBCC propulsion system is covered next in some detail. An overview for the low speed system is given; then its development is discussed (starting with initial layout and leading to more detailed analyses performed and results). The low speed system portion is wrapped up with lessons learned and summary. Finally, an overall summary and lessons learned so far for the JSS are given as well as work planned to complete the study.



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United States
Air Force

**NASA/Air Force
Joint System
Study**

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**Presented by Christopher Snyder
Turbine Engine Technology Symposium
Dayton Convention Center, Dayton, OH
September 16, 2010**

Distribution Statement A: Approved for Public Release

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◆ Joint Systems Study (JSS)

- Description & Planned Efforts / Present Status
- Ground Rules and Assumptions

◆ NASA TBCC TSTO Concept (RALV-B)

- RALV-B design evolution was covered at the FAP Annual 2009
 - Upper stage is reusable lifting body, all rocket (X-34 heritage)
 - Vehicles changed as requirements changed (payload, orbit, etc.)
 - Will not be repeated here (time constraints)
- Mission Profile & vehicle layout / packaging
- High Speed Propulsion (work performed & lessons learned)
- Low Speed Propulsion
 - System Overview
 - Level 1 Information
 - Level 2 Efforts
 - Lessons Learned / Summary

◆ Overall Summary



- Examine performance, operability and uncertainty of unmanned, fully reusable, airbreathing based two-stage-to-orbit (TSTO) launch vehicle concepts (trade) vehicle concepts
 - NASA will provide: TBCC booster, rocket orbiter
 - Air Force will provide:
 - Rocket booster, RBCC orbiter
 - Rocket booster, Rocket orbiter
 - Perform “Level One” analysis on the other’s concepts
 - Highlight tool capabilities and shortfalls
 - Identify areas for joint efforts (tools, concepts, etc.)
 - Perform Level Two analyses on own concepts (as time, resources allowed)
 - Note system changes
 - Deficiencies in level one analyses (improve future level 1 efforts)
- Agree on Common Ground Rules and Assumptions
 - Mission(s) of interest
 - Not unfairly biased (favor or penalize) any particular vehicle or concept
- Concept of Operations
 - Develop Operations Model
 - Leads to development, refurbishment, and life-cycle costs

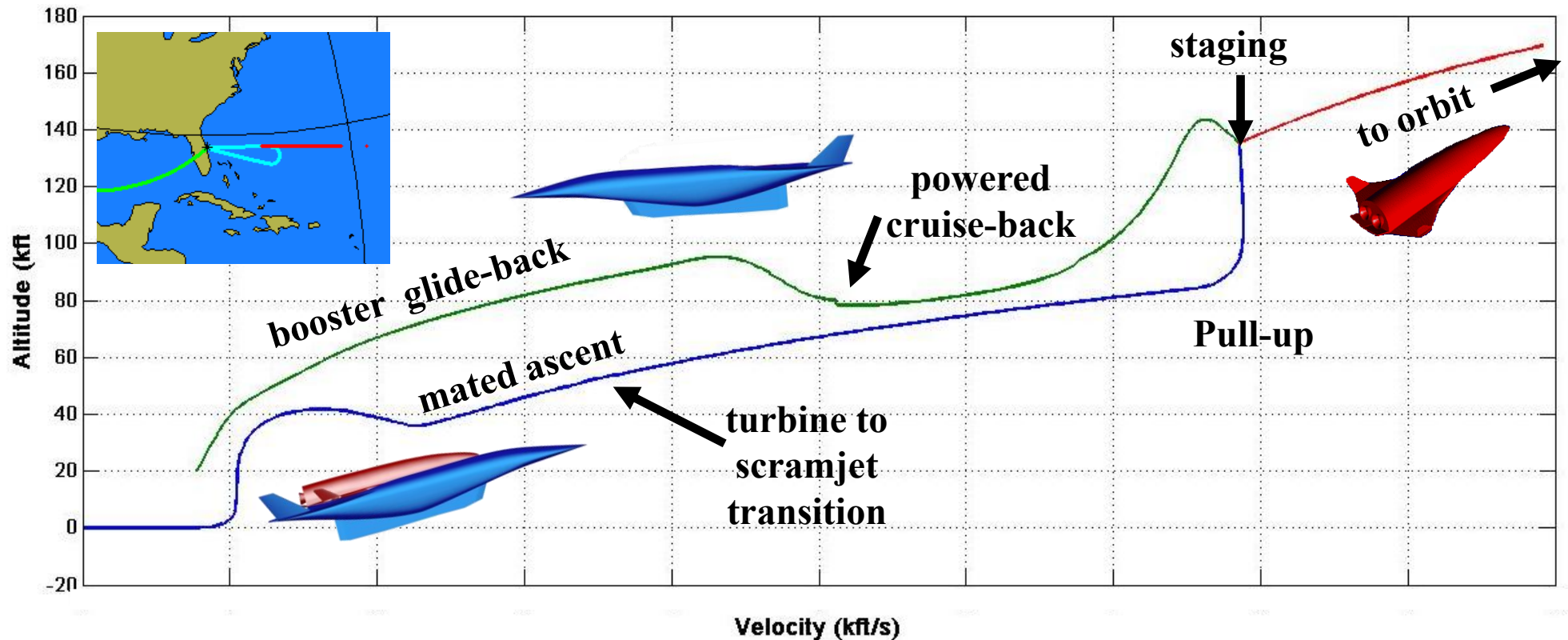
*For NASA – exercise for tool assessment & development, identify generic technology gaps, **not** choose vehicle type or concept*



JSS Ground Rules and Assumptions

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- ◆ **NASA Launch Vehicle Concept**
 - Unmanned, Fully Reusable, TSTO, TBCC/Rocket
- ◆ **Technology Readiness Level (TRL)**
 - Technology Availability Date (TAD) – 2018 (TRL Six)
 - Initial Operating Capability (IOC) – 2026
- ◆ **System Deployment**
 - Launch Site – Kennedy Space Center
 - Landing Site – Kennedy Space Center
 - Booster and orbiter nominally return to launch site (RTLS)
- ◆ **Payload Delivered**
 - Mass – 20,000 lbs (up and down)
 - Dynamic Envelope – 12 ft dia. x 30 ft long
- ◆ **Target Orbit**
 - Altitude – 100 x 100 nmi
 - Inclination – 28.5°
- ◆ **Cross-range on entry – 1200 nmi**
- ◆ **Maximum sensed acceleration – 5 g's**
- ◆ **English units used for data exchange**
- ◆ **Mission duration for orbital stages**
 - 24 hours (launch to landing)
- ◆ **Launch Window – 60 minutes**
- ◆ **Mass Growth Allowance**
 - Airbreathing stages – 15% dry mass
 - Rocket stages – 15% dry mass
- ◆ **Propellant Margins**
 - Airbreather stages – 1% margin on fuel
 - Rocket stages – 1% margin on fuel and oxidizer
- ◆ **Orbiter Delta-V**
 - OMS
 - De-orbit - 170 ft/sec
 - Circularization – as required
 - On-orbit – not defined
 - RCS – 150 ft/sec



◆ **Mated ascent includes:**

- Turbine and rocket powered take-off and transonic push-through
- Transition to scramjet operation
- Powered pull-up to staging

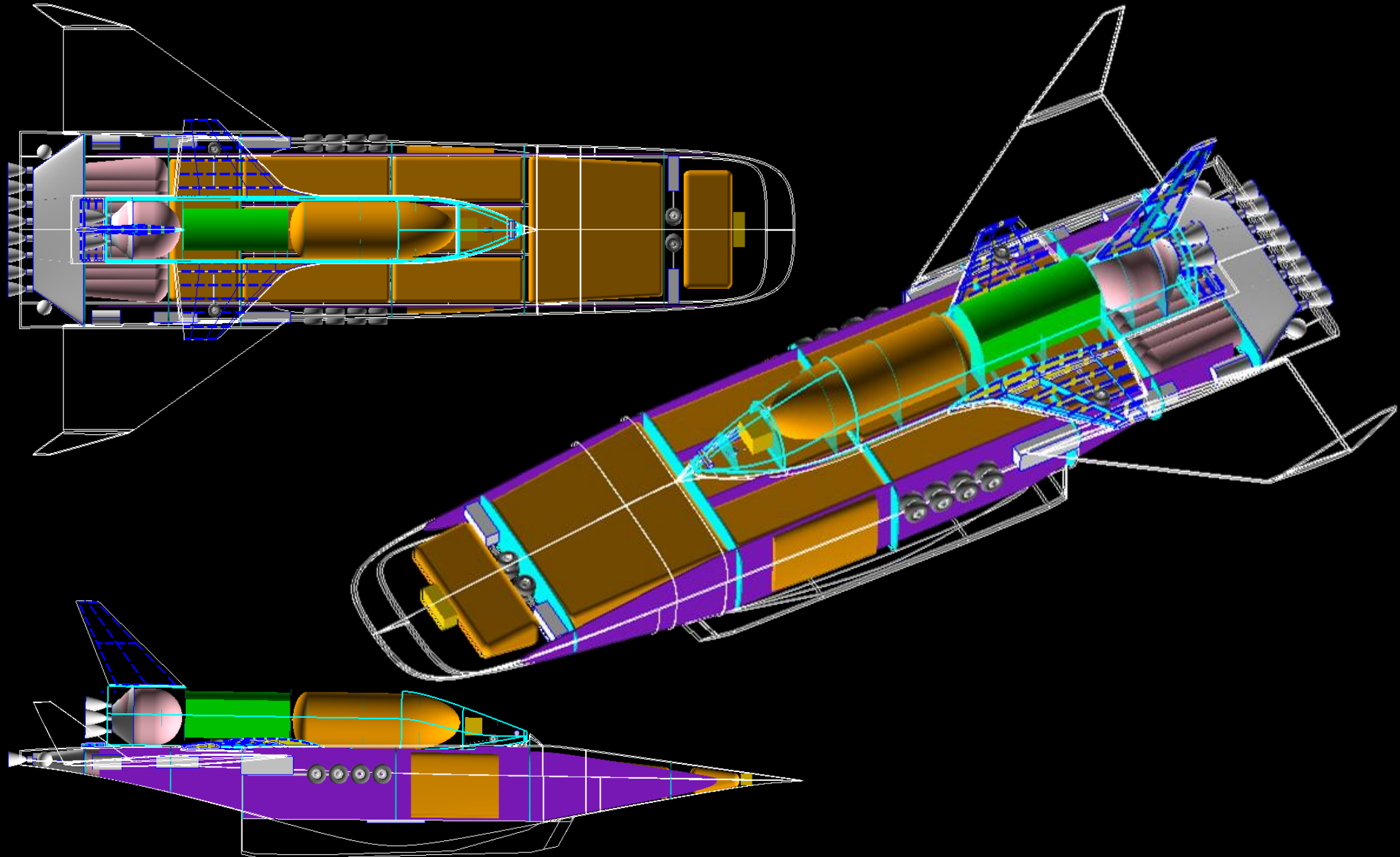
◆ **Booster fly-back includes:**

- Complex maneuver to recover from staging and attain heading alignment for RTLS
- Scramjet powered cruise-back
- Glide back to Terminal Area Energy Management (TAEM) and dead stick landing

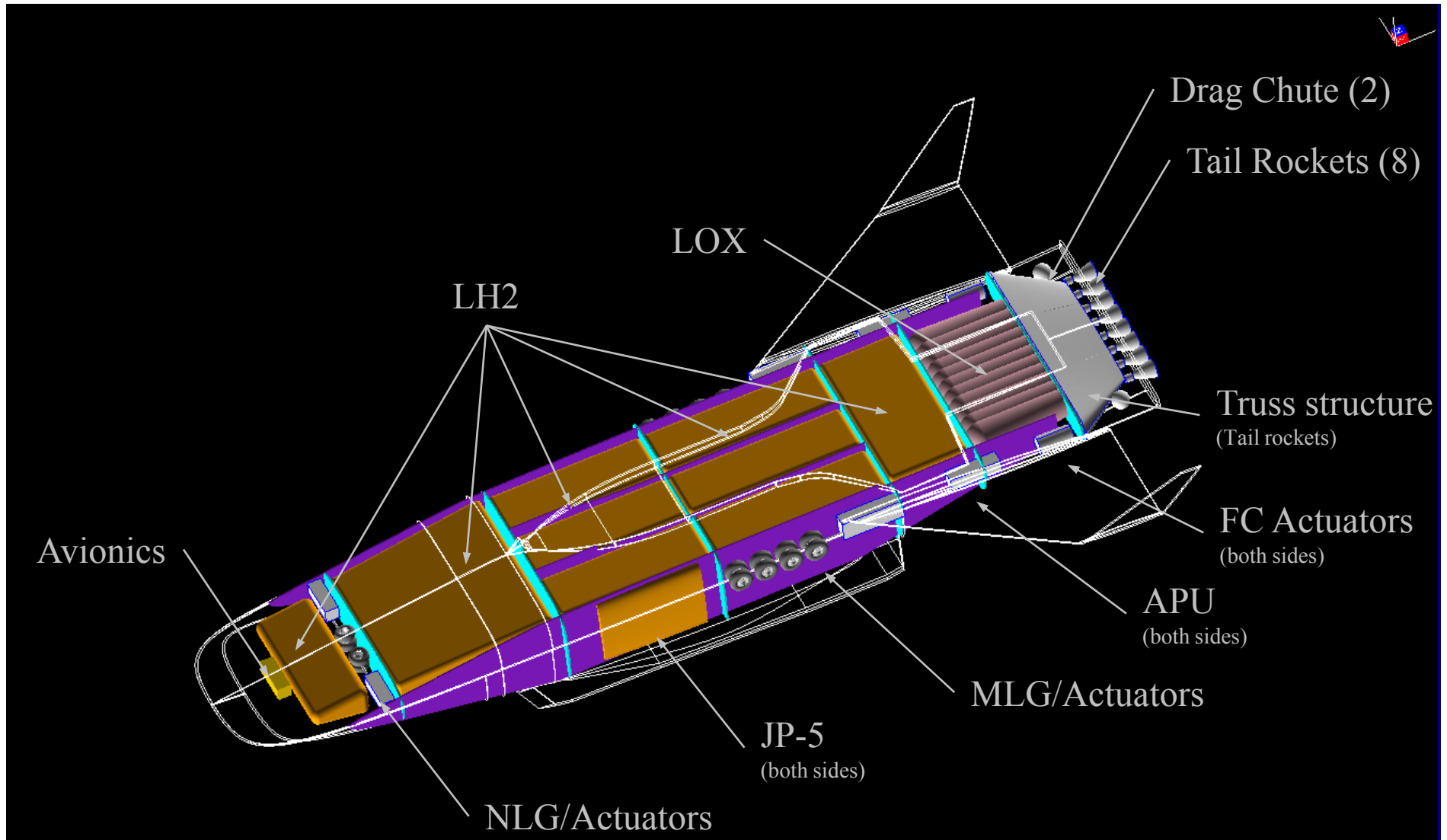


RALV-B

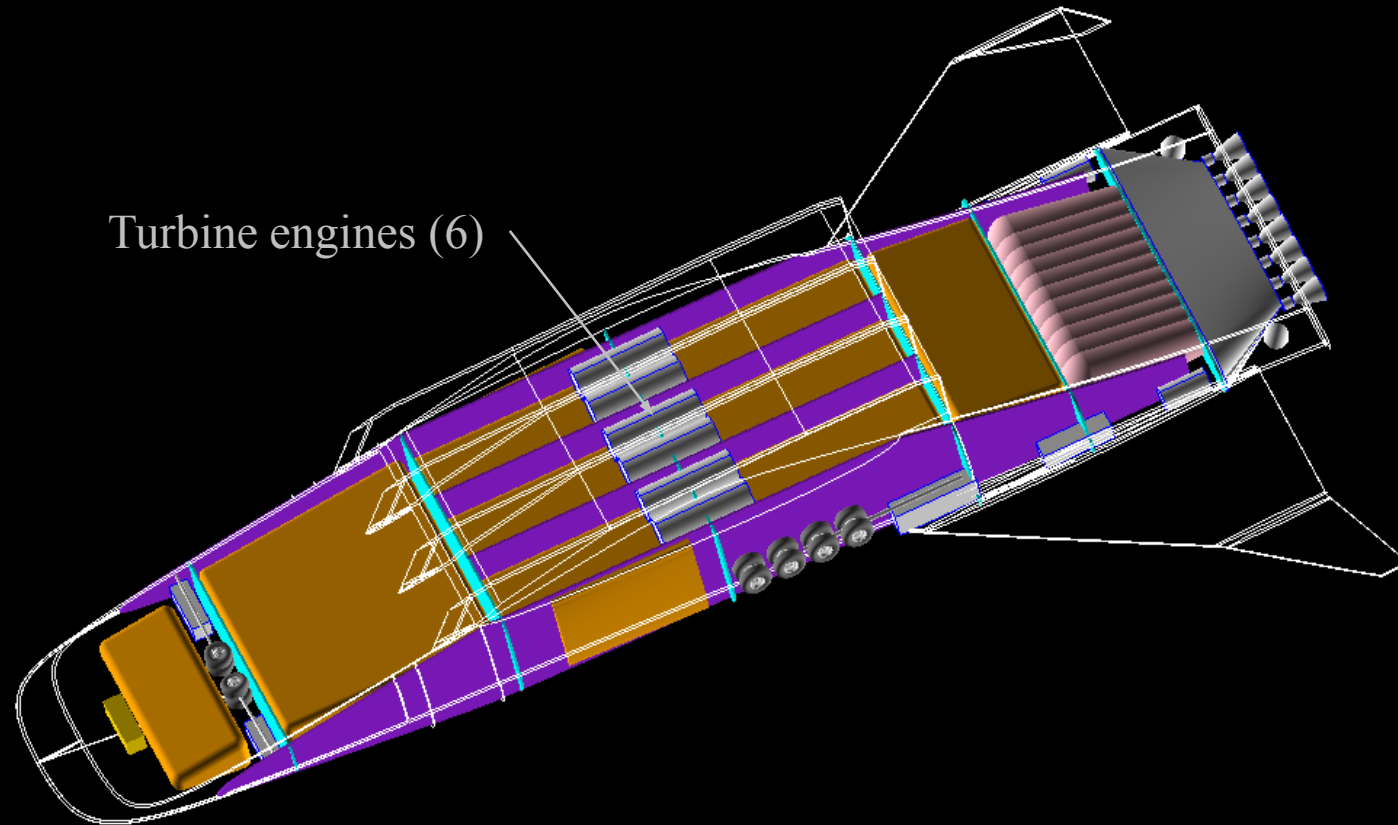
Internal layout and Packaging



RALV-B1 – Booster Top view



RALV-B1 – Booster Bottom view





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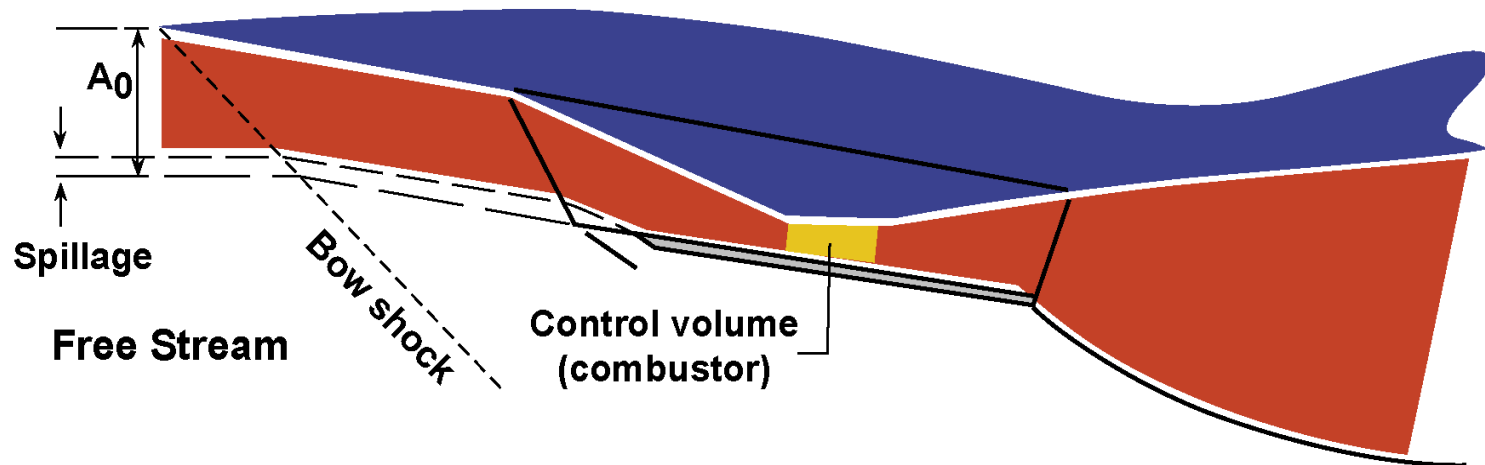
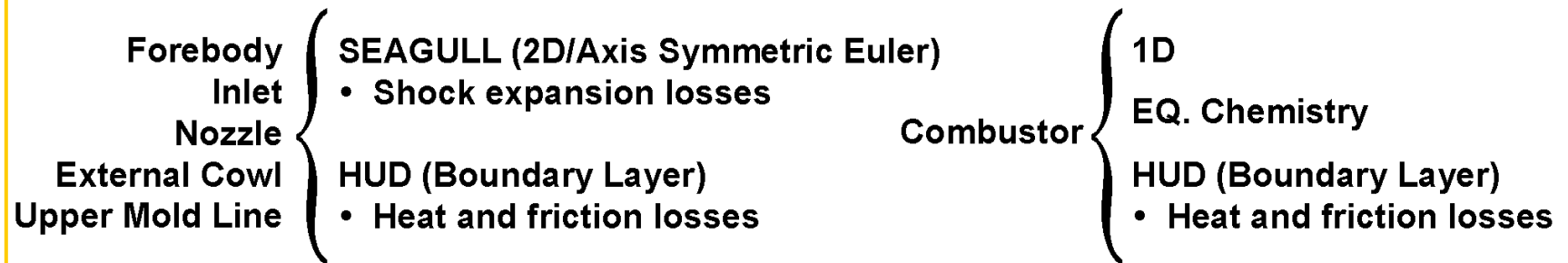


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High Speed Propulsion

(Highlights *shamelessly* stolen from Shelly Ferlemann's slides)

Tip-to-Tail Propulsion Analysis (2 Min. per Solution)



Input:

- Geometry
- Boundary conditions
- Fuel schedule
- Lifting/trim wings C_L and C_D

Additional Modeling:

- ETAKE Penalty
- 3-D Spillage
- Combustion Efficiency Curve
- Base Pressure
- 3-D Nozzle Expansion



- Attempt to use MDOE to generate data high speed propulsion data. MDOE process and data would lend itself to:
 - Easier to design engine at vehicle level
 - Can account for aero forces and structural/ thermal input ...etc.
 - Can change constraints and not have to go through long design process
 - Can extract statistical data about how independent variables affect multiple responses
 - Can give more insight to entire vehicle design team instead of all information with residing with propulsion discipline
 - Easier to perform technology trades
- Data generated and regression equations generated. Although R^2 values were high (.996 for 500 case Axial Force), the Regression equations at the extremes of responses did not represent data well. Even giving the wrong trends!
- New dataset for mission analysis generated using lessons-learned from RALV-A as starting point (with limited scaling capability). Resulting data addressed most concerns (shortfalls) from previous iteration. Continuing to work MDOE methodology to address shortcomings uncovered.



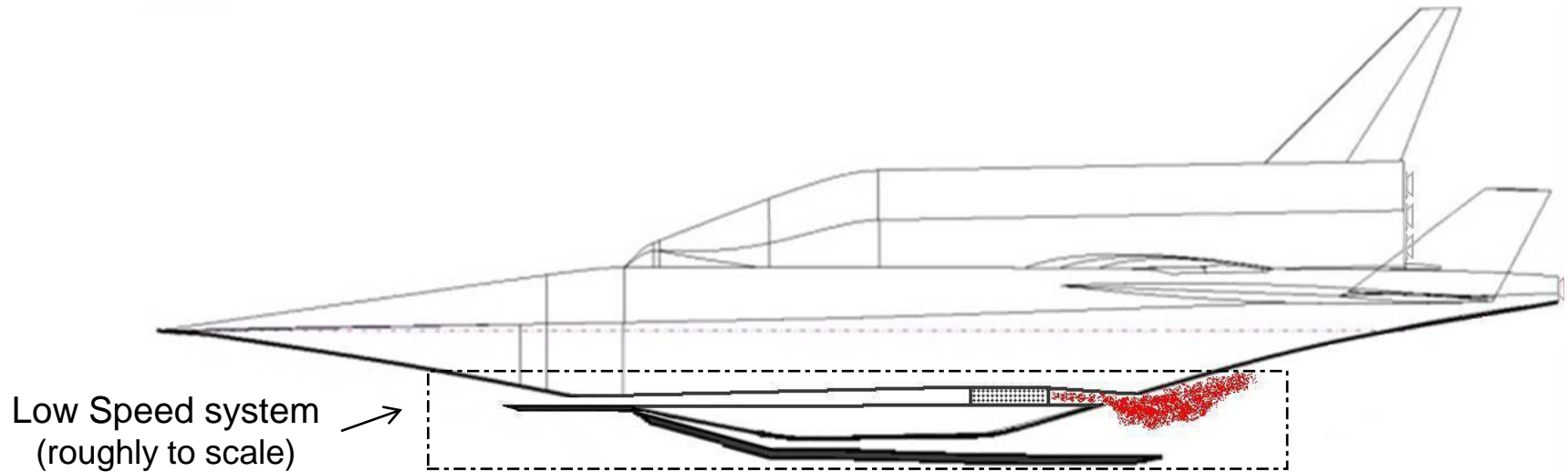
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Low Speed Propulsion



♦ Integration of gas turbine engine (GTE) with vehicle and high-speed flow path **THRUST is KEY!**

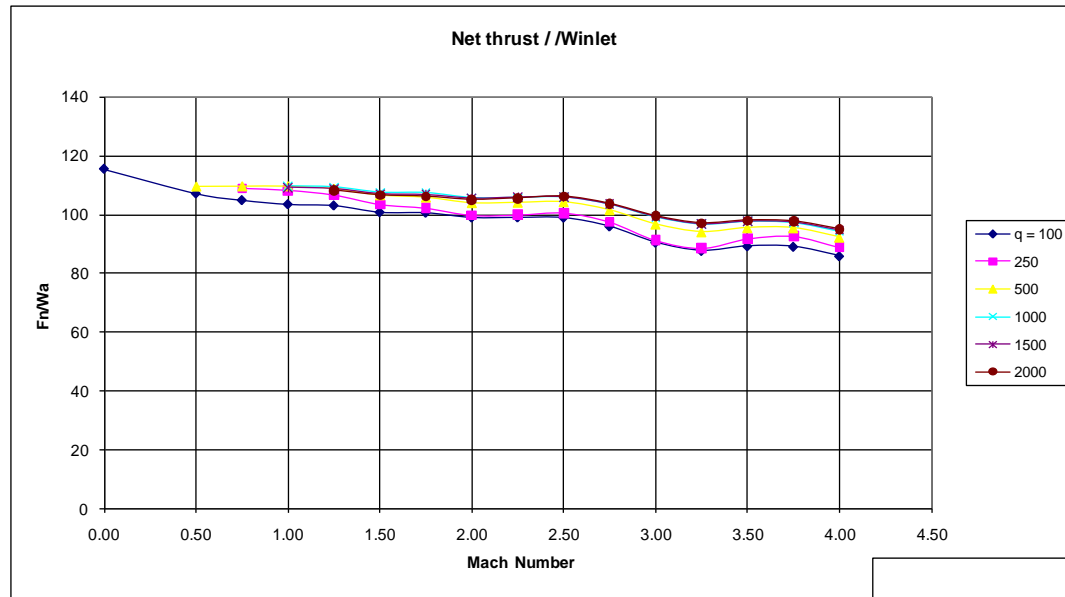
- Over / under with separate inlets, complicated problem to analyze (interactions)
- Level 1 datasets do not include many effects (i.e. moments, spillage, etc. –) results from level 2 analyses critical to understand and model correctly (will be discussed in later charts)

♦ Gas Turbine “level 1” databases includes a generic, high-speed GTE, RTA engine and “F135-like” cycle. Includes axial forces, fuel flow, and also other information

- Scale data with size (airflow), includes an engine weight
- Corrections available for inlet and nozzle performance estimates that differ from initial assumptions (methodology from Hess & Mumford).
- Also includes internal properties (W , T , P , γ) for additional analyses.



Low Speed Propulsion Example GTE Data (Level 1)



Wa 220 lbm/s (SLS)
 Dia 42"
 Length 147" (gte) + 180" (aug)
 Weight 3500 lbm

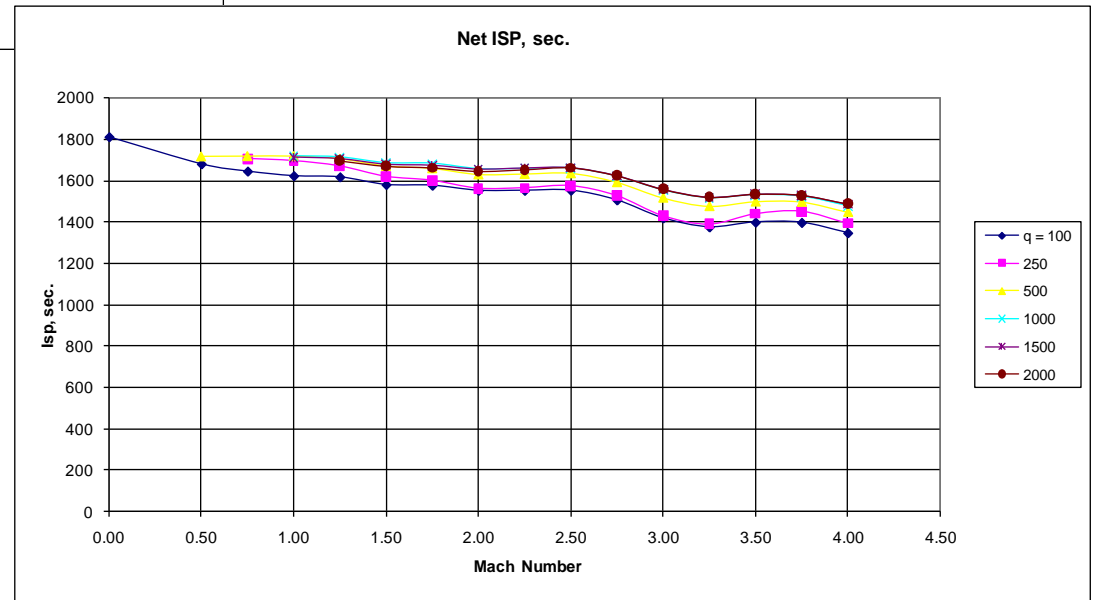
Scaling

Constant T/W, L/D (gte), L (aug)

$Wa \propto (\text{Diameter})^2$

$F_n \propto Wa$

(although length is a "soft number")



From Generic, high-speed gas turbine engine spreadsheet, HC fuel: many more parameters available



Low Speed Propulsion Boeing GTE Integration Work (take Level 1 data → 2 +)

- ◆ Integrate gas turbines & perform inlet / nozzle analyses
- ◆ Conduct analysis at Mach 1.2 and Mach 3.5 to address two most critical modes (transonic pinch & transition)
- ◆ Freeze high speed flow path geometry
- ◆ Build-up complexity
 - Flow path modeling (go from “easy” to more difficult)
 - Inlet CFD only
 - Inlet CFD + turbine & ramjet models
 - Inlet CFD + turbine & ramjet models + nozzle stream tube analysis
 - Inlet CFD + turbine & ramjet models + nozzle stream tube filling with external burning
 - Inlet CFD + turbine & ramjet models + nozzle CFD
 - Untrimmed, axial force only, then add vertical & moment
- ◆ Other study variables to consider:
 - ~~Rocket use to maintain axial acceleration?~~
 - Look at high speed flowpath open vs. closed
 - Look at external burning vs. ramjet operation vs. no burning
 - Flap scheduling (during transition first & then low speed geometry changes...)
 -

Ongoing / Results were instructive to level 1 efforts



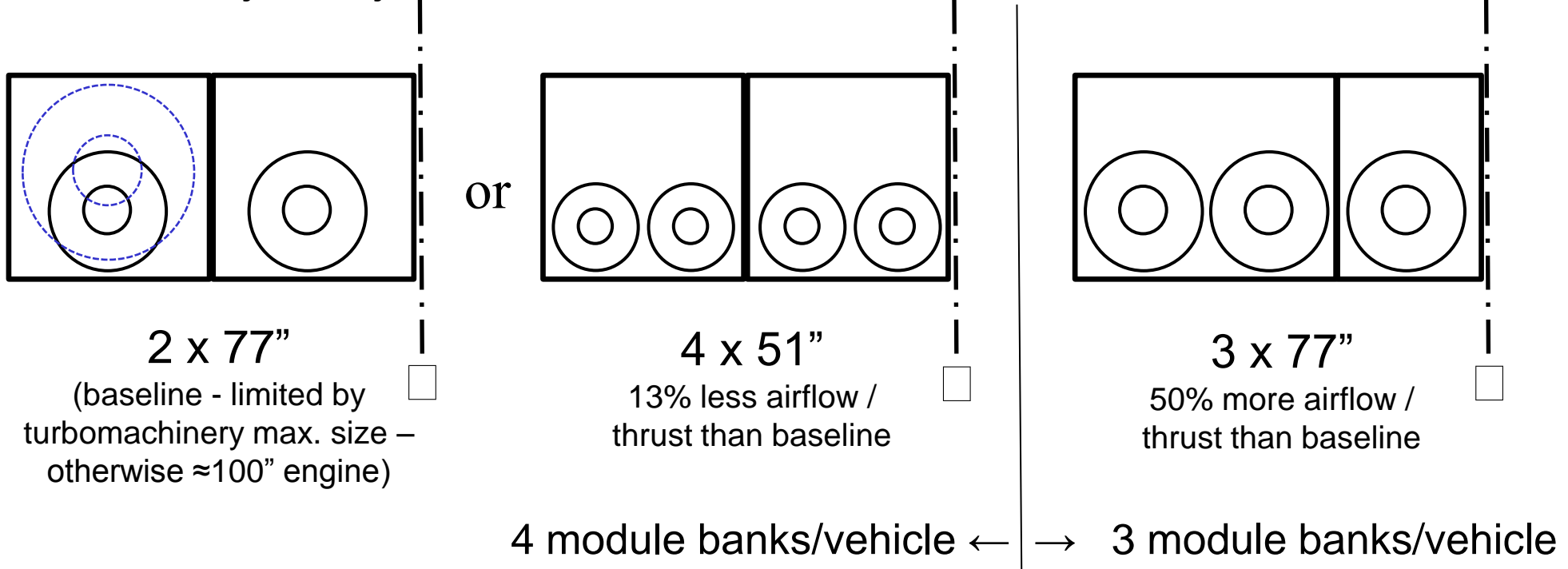
Initial design resulted in a significant shortfall in GTE performance.

Level 2 analyses suggested areas to reduce shortfall (overview here, further details on following slides – nozzle's main area of concern)

- ◆ **Number of high-speed flow paths and gas turbine fan to maximum engine diameter must be coordinated to maximize system performance**
 - Minimize unused space
 - Maximize gas turbine airflow (and therefore thrust)
- ◆ **Use high-speed flow path (to flow some air) to improve pressures around vehicle**
 - Gas turbine exhaust is inadequate to fill nozzle area, especially transonically – large (nozzle) base drag area (nozzle optimized for HS propulsion)
 - Judicious use of high speed inlet helps fore-body pressures (and drag surface areas) a little and really helps fill nozzle area and minimize adverse pressure regions (indicates potential benefit of using HS nozzle flap for additional flow control and performance)
- ◆ **External Burning**
 - Alternative / additional method to help pressurize nozzle region
 - Easy to apply (at level 1 analysis detail), but question of level 2 modeling fidelity
 - Applicable during certain flight regimes; there are propellant and complexity costs



Low Speed Propulsion Steps To Improve GTE Sizing: HS Flow Path Arrangement For GTEs

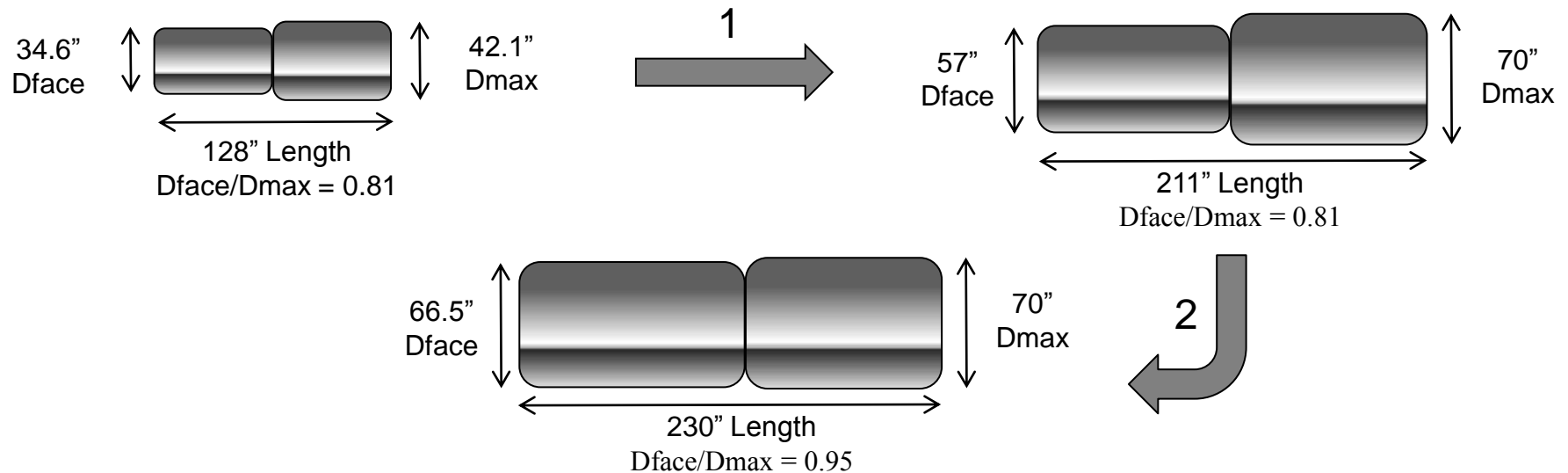


- ◆ **Original HS flow path assumed 4 modules banks (2 per side of vehicle) of 2 ramjet / scramjet flow paths per module. Wall that splits module into 2 flow paths does not extend into LS system area. Study assumption (due to turbomachinery limits) - GTE size limited to maximum of 70\", and only 1 row across (GTEs are not stacked 2 rows high).**
- ◆ **If assume 3 (total per vehicle), wider RJ/SJ module banks, and center support piece does not protrude into GTE area, optimizes number / size of potential GTEs**



Low Speed Propulsion Steps To Improve GTE Sizing Engine Configuration

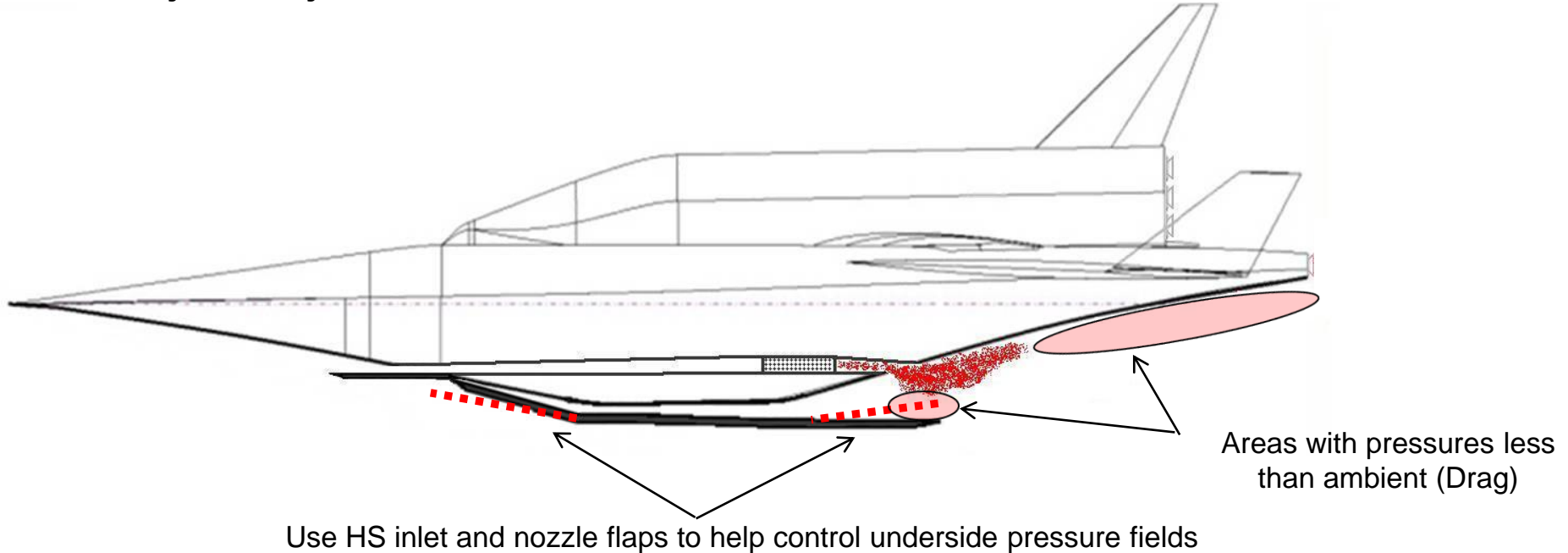
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◆ Original GTE layout scaled to fit maximum diameter (to 70" – study assumption for limit on turbomachinery sizes) (scaling #1)

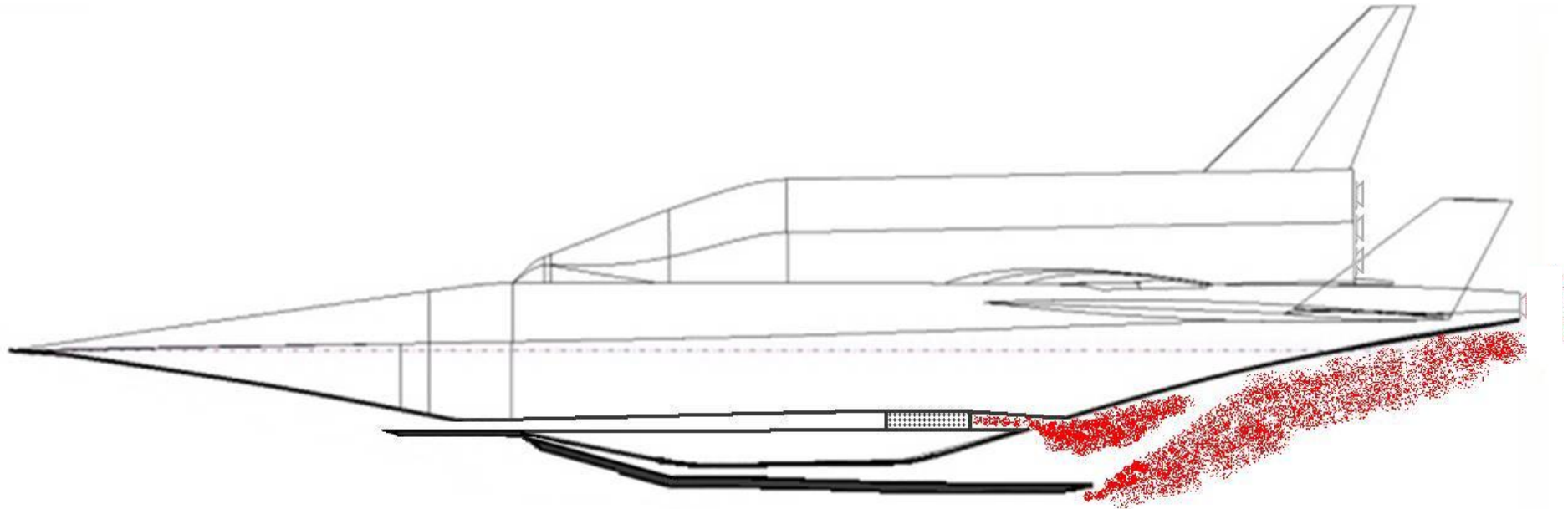
- Original ratio of Dface to Dmax was severely limiting airflow capacity of GTE (for cross-sectional area available - 81%).
- Reviewed engine heritage: Layout was to use available assets for wind tunnel test. No optimization of flow areas and various accessories for our application.
- Other engines and previous studies suggest re-arrangement could reasonably enable D_{face}/D_{max} up to 0.95 (resulting in an over 30% increase in airflow and thrust). Packaging limit is truly engine width (within the 70" turbomachinery limit). Acknowledge that this will have to be confirmed in level 2 GTE analyses. Some accessories could be arranged above or below GTE flow path and probably some growth in length (of which there is plenty of room in the present configuration). (scaling #2)

Low Speed Propulsion HS Flow Path Scheduling To Improve Pressure Fields



- ◆ **ISSUE:** With HS inlet closed, there is insufficient GTE flow to fill the nozzle (base) area, thus it becomes a large drag surface (not captured in level 1, GTE analysis).
- ◆ **SOLUTION:** There is an optimum amount to open the HS inlet for some airflow in the HS flow path (before operation of the ramjet / scramjet)
 - Helps reduce fore-body pressures and forward facing surfaces (reducing fore-body drag)
 - Also helps fill the nozzle base area close to ambient pressure (eliminate / greatly reduce nozzle adverse drag and moments).
 - Too much HS flow can un-start LS inlet and possibly force normal shock for flow in front of vehicle (penalizes GTE performance and increase fore-body drag significantly).
- ◆ **Requires level 2 analyses to capture effects “properly” (at least with present level of understanding).** Analyses are presently part of Boeing contracted effort.

Low Speed Propulsion Use External Burning Help Pressure Nozzle Region



- ◆ **Fuel external (non-GTE) flow to help fill nozzle area unfilled by GTE system** (Use HS flow path and / or vehicle underside external flow)
 - Pros
 - Easy to do (analytically)
 - Potential to improve nozzle pressure field close to ambient
 - Better “thrust” Isp versus tail rocket (reducing low speed thrust deficit and adverse vehicle pitching moments)
 - Cons
 - Additional system complexity (additional injectors, flame holders, etc.)
 - Propellant cost



- ◆ **Some LS propulsion gains achieved after review of initial assumptions (re-learn from previous studies)**
 - **Find “low hanging fruit”** - after significant shortfall noted, reviewed previous studies to note differences from this effort (are assumptions limiting us?)
 - Gas Turbine assumption for D_{face}/D_{max}
 - Limit for gas turbine maximum turbomachinery diameter?
 - **HS and LS arrangements must be coordinated** - choose number of HS modules and structure to optimize GTE number and size
- ◆ **LS propulsion sizing and integration is not optimum.**
 - Level 1 methods appear inadequate to capture many LS system dependencies (vehicle adverse forces and moments) required to optimize overall performance.
 - Judicious operation of the HS flow path can improve fore-body flow and pressure fields. **More importantly**, this flow and external flap position can significantly mitigate adverse nozzle pressure fields. Level 2 analysis required to properly quantify effects. (**NASA tool deficiency**).
 - Assuming external burning can effectively mitigate effects of adverse nozzle pressure fields (vary propellant flow requirements to estimate sensitivity – is within level 1 analyses). But increases analysis uncertainty.



♦ **NASA's Airbreathing TSTO vehicle continues to evolve**

- Systems analysis team is coming up to speed (some relearning / work “smarter”)
- Computers continue to get faster, but still can't afford 3-D CFD everywhere to capture all effects. Tools (especially for the low speed system) have deficiencies that have strong design ramifications. Some assumptions (external burning) can be used to mitigate some tool limits (adds complexity / uncertainty)

♦ **Level 2 analyses on overall vehicle will not be performed on the NASA TSTO concept** (originally planned in Joint System Study)

- Design is not optimal enough to warrant level of effort required for higher fidelity analyses for all systems. Redirect to more level 1 and technology trades
- Will use limited, higher fidelity analyses to help supplement level 1 efforts (especially to try to minimize certain areas of analysis uncertainty)

♦ **JSS has been very effective (instructive?) in pointing out areas of analysis immaturity (tool development requirements)**

- Work is continuing to develop and integrate tools (especially where there is the most uncertainty).
- A lot of good work, but still early in the design evolution. We need better methods to enable redesign and update performance, sizes and weights, quickly, accurately, etc.



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